A new, simple, test-set for on-wafer characterization of millimeter-wave electro-optic devices

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Abstract—**A simple approach is described for the on-wafer and in-package electrical and electro-optic characterization of electro-optic components, such as electro-optic modulators, up to 40 GHz. The technique makes use of a two-port electrical measurement on a device obtained by connecting a calibrated high-speed photodetector to the optical output of the DUT. From the measurement of the electrical S_{21} and the detector calibration curve, the electro-optical transmission coefficient is derived. The calibration of the on-wafer test set is carried out through the RSOL technique. The accuracy and repeatability of the proposed method is shown to be comparable with the ones of commercially available instrumentation, and the frequency bandwidth, once that the high-frequency responsivity of the photodetector enables the network vector analyzer (NVA) to operate above its noise floor, is only determined by the NVA bandwidth. Some results and comparisons are presented concerning packaged and on-wafer $LiNbO_3$ modulators.**

I. Introduction

During the last few years, considerable interest has been placed on the experimental characterization of electro-optic components at increasingly high frequency. Some general approaches have been proposed to this aim, based on the so-called Electro-Optic (e/o) Network analyzer concept [1,2]. This approach makes use of a bilateral e/o network [3,4]. Although this solution is potentially able to solve the problem, the implementation is rather complex and the calibration procedure relies on optical standards whose behaviour in not always well known; besides, the published results are limited to 10 GHz. The same kind of limitation is presented by commercially available equipments for the electro-optic transmission measurement (e.g. HP8703A), whose maximum frequency is limited to 20 GHz.

Recently, there has been a growing interest in the development of electro-optic components, in particular modulators, with modulation bandwidths in excess of 40 GHz. The electro-optic characterization of these devices poses some clear challenges; besides, both on-wafer and packaged device characterizations are often required to assess the effect of package and connectors on the modulator performances.

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Following these considerations, we developed a new simple characterization technique suitable for electro-optic devices. The proposed method can deal both with on-wafer and on-package electro-optic devices, and avoids the use of exotic calibration standards, since it exploits the ones classically used for RF measurements. For on-package measurements, the RF signal is injected into the device through a coaxial connection, while, for on-wafer characterization, the RF modulating signal is directly brought on chip through a coplanar probe. The RF-modulated optical signal exiting from the tested device is then sent to a calibrated photodetector that takes care of the RF recovery, thus making the RF signal available on a coaxial connector at the photodetector output, see Fig. 1. The electrical input reflection coefficient (S_{11}) together with the electrical transmission coefficient (S_{21}) from the DUT input to the photodetector output can be measured directly, while the electro-optical transmission coefficient can be derived by deembedding, from the measured electrical S_{21}, the relative photodector responsivity given by its calibration curve.

Concerning RF measurements, the system is a two-port and, as well known, it can be easily characterized using a vector network analyzer, once the reference planes are properly placed at the system ports through the calibration of the system. When the RF input is through a coaxial connector, the calibration can be carried out using whatsoever technique (e.g. TRL, LRM, SOLT). On the contrary, problems arise when the RF input is on a coplanar probe. In fact, all conventional calibration approaches for two-port devices make use at least of one well defined, two port standard, usually referred as *Thru*, which is to be connected between the two RF ports for the netwowk analyzer calibration procedure. Unfortunately, such a well-characterized two-port standard is not available when the two ports are of different type, as in our case for on-wafer measurements. This problem can be overcome using the so-called RSOLT method, as discussed in Sec. II.

The main advantages of the proposed system and calibration technique are the test set simplicity compared to other electro-optic measurement system; the high calibration accuracy without making use of optical standards or cumbersome deembedding procedure; the low cost, since the main parts of the measurement setup are an ordinary network analyzer with a simple photodiode. Moreover, the upper frequency limitation of the system is only dictated by the frequency bandwidth of the analyzer and by the available photodiode, whose response, being deembedded from the measurement, must not be necessarily flat up to the maximum operating frequency.

The paper is structured as follows. Section II is devoted to describing the measurement set-up and the calibration technique. In Sec. III results from the present set-up are compared to those obtained from a commercially available electro-optic characterization system up to 20 GHz and the set-up repeatability is discussed; some examples of characterization up to 40 GHz are finally presented for electro-optic modulators both in package and on chip.

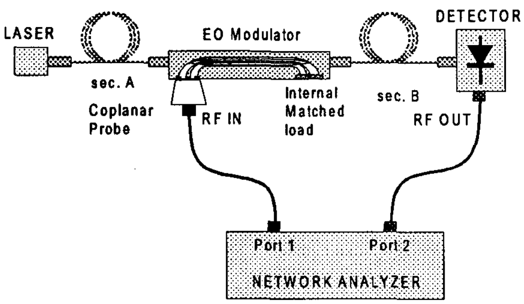

Fig. 1. Measurement set-up.

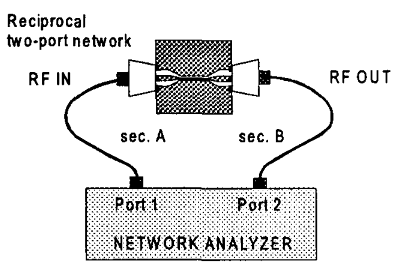

Fig. 2. Calibration procedure.

II. The Measurement System

The measurement system, shown in Fig. 1, uses a high-speed calibrated photodiode, produced by Optospeed (Model PD-MH-40A) and characterized by NIST, to detect the optical modulated signal and a traditional network analyzer to excite the modulator and measure the photodetector output. The system can perform the electrical S_{11} and the electro-optic S_{21} measurements through a particular application of the so called RSOL calibration [5]. The same setup was also exploited for in-package characterization; in this case both RSOL and conventional calibration procedures have been tested and applied, giving identical results. In what follows, the attention will be focused on the on-wafer system.

As shown in Fig. 1, the microwave reference planes are placed one at the on wafer probe tips (sec. A, port 1), and the other at the coaxial output of the photodiode (sec. B, port 2). Traditional calibrations (e.g. TRL, SOLT) are not applicable since they all required a THRU (i.e. an ideal zero length connection) between the two different connector type ports or at least a cumbersome de-embedding procedure to include the coplanar probe effect.

The RSOL calibration [5] procedure allows to overcome this hindrance, since it uses an undefined passive reciprocal network instead of the fully known THRU standard. This technique is appropriate to our case, for which one port of the device under test is on the coplanar input of an electro-optic modulator, and the other port is on the coaxial K connector of the photodiode used for RF detection. During calibration, simply another probe, cascaded with a coplanar transition, was used as the two-port reciprocal network, as shown in Fig. 2.

The one-port connections, further required for this kind of calibration to complete the error box extraction procedure, are three known standards for each of the two-ports. At port 2, a set of traditional coaxial standards was used (short, open and load), while the same standard, in on-wafer form, were connected to port 1. Finally, the electro-optic calibration is completed by combining the photodiode response provided by the NIST calibration (see Fig. 3) with the error coefficient given by the procedure described above.

III. Analysis and Validation

Figure 6 and Fig. 7 show the electro-optical transmission coefficient and the electrical reflection coefficient of an electro-optic $LiNbO_3$ modulator. In order to assess the repeatability of the proposed set-up, several measurements were carried out with the same and with different calibrations, the maximum measurement difference for the input reflection coefficient were less then 8 % while, concerning the transmission coefficient, a maximum difference of 4 % were found; the higher maximum value for the input reflection coefficient is clearly related to the presence of reflection zeros.

To validate the presented approach, some measurements

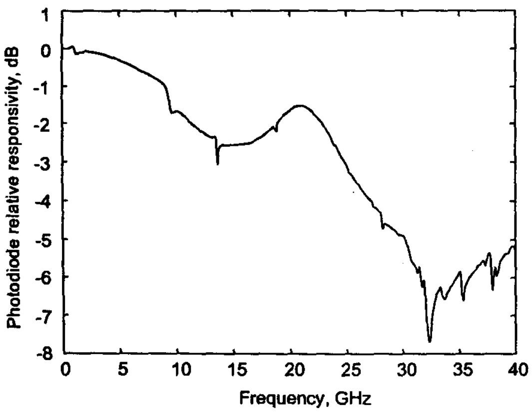

Fig. 3. NIST photodiode optical-electrical response.

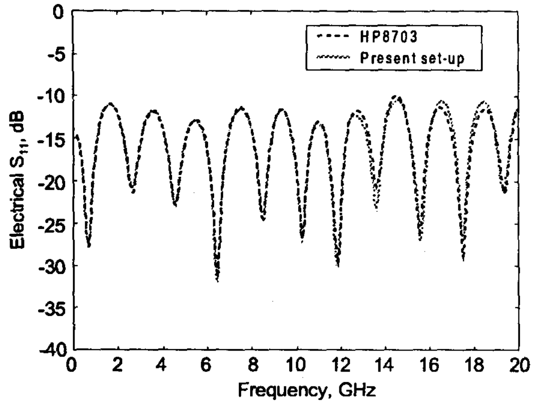

Fig. 4. Comparison between measurements of S_{11} on an electro-optical modulator up to 20 GHz. Continuous curve: this set-up, dotted curve: HP8703A.

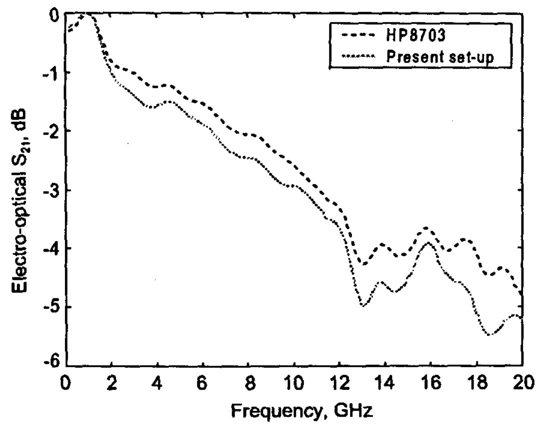

Fig. 5. Comparison between measurements of the electro-optical S_{21} on an electro-optical modulator until 20 Ghz. Continuos curve: this set-up, dotted curve: HP8703A.

of electro-optic modulators were made and the results compared with the one given by a conventional electro-optic measurement system HP8703A. Since this test set only supports coaxial RF input, the comparison was made on a packaged device. The measured electrical input reflection coefficient up to the maximum HP8703A operating frequency (20 GHz), is reported on Fig. 4; the agreement is very good on the whole frequency range, with a maximum difference below 0.2 dB.

Figure 5 shows the electro-optic S_{21} as measured by the present set-up (continuous line) and the one obtained with the HP8703A measurement system (dashed line). The electro-optic S_{21} is, as done usually, normalized to the low frequency (1 GHz) value. The agreement is quite good at very low frequency, and the discrepancy between the two measurements is within the expected uncertainty. In fact, the uncertainty of the measured electro-optic transmission coefficient is affected, in the present approach, mainly by the photodiode calibration curve, which, in our case, was ± 0.5 dB on the whole frequency range [6]. The same uncertainty is reported for the HP8703A electro-optic network analyzer [7].

The system was also tested by measuring electro-optic modulators up to 40 GHz, both in packaged form and on wafer. It important to notice that the maximum frequency is, at least in principle, only limited by the network analyzer bandwidth. The photodetector bandwidth can be lower than the maximum operating frequency, provided that the high-frequency responsivity allows the network analyzer to operate well above its noise floor.

Figure 6 reports the frequency behaviour of the electrical input reflection coefficient up to 40 GHz, while Fig. 7 shows the electro-optical transmission coefficient of same device, in packaged form. Concerning on-wafer measurement, the electrical input reflection coefficient and the electro-optic S_{21} for a modulator with coplanar RF input, and for the same frequency range, are reported on Fig. 8 and Fig. 9, respectively.

IV. Conclusions

The characterization of electro-optical devices up to 40 GHz has been addressed through a new, simple technique, making use of a network analyzer and a calibrated photodetector. The accuracy and repeatability of the method are

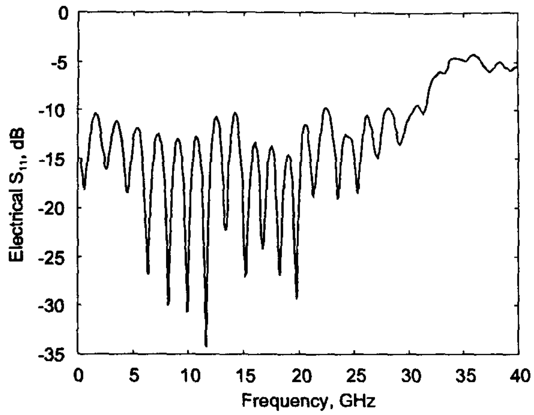

Fig. 6. Electrical S_{11} of an electro-optical modulator (in package).

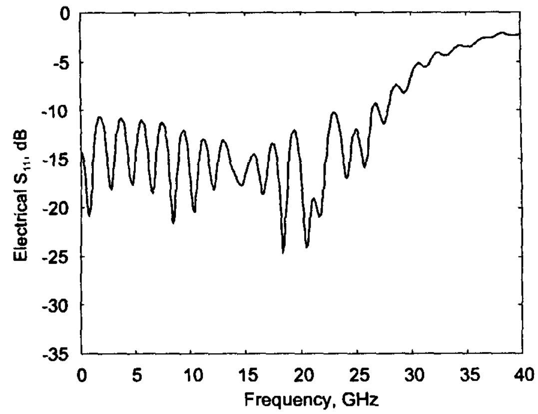

Fig. 8. Electrical S_{11} of an electro-optical modulator (on wafer).

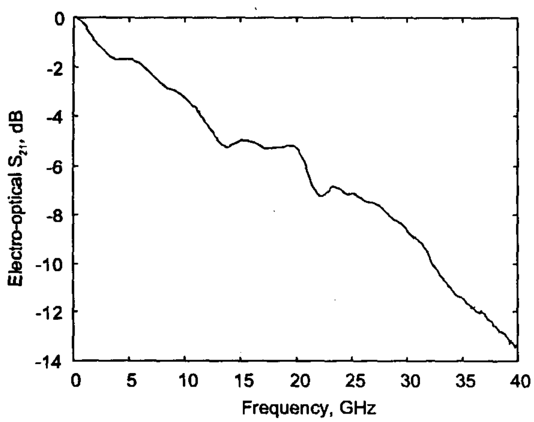

Fig. 7. Electro-optical response S_{21} of an electro-optical modulator (in package).

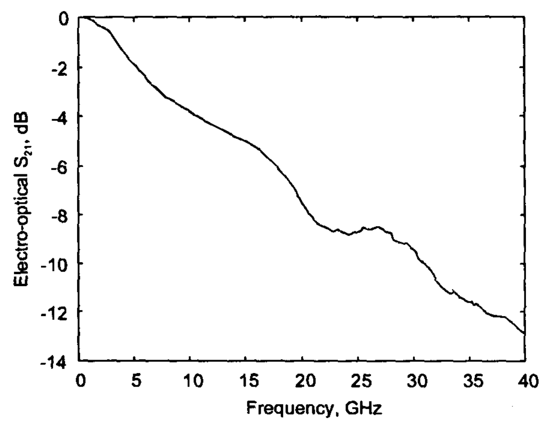

Fig. 9. Electro-optical response S_{21} of an electro-optical modulator (on wafer).

comparable to commercially available equipment, with the advantage that the bandwidth is only limited by the network bandwidth and by the photodetector response.

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